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**MEASUREMENT OF TOTAL ELECTRON CONTENT OF
MIDLATITUDE IONOSPHERE AND PROTONOSPHERE VIA
FARADAY ROTATION AND GROUP DELAY TECHNIQUES USING
TRANSMISSION FROM GEOSTATIONARY SATELLITES ATS-3 AND ATS-6**

(NASA-CR-168852) MEASUREMENT OF TOTAL
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AND PROTONOSPHERE VIA FARADAY ROTATION AND
GROUP RELAY TECHNIQUES USING TRANSMISSION
FROM GEOSTATIONARY (Alcorn State Univ.,

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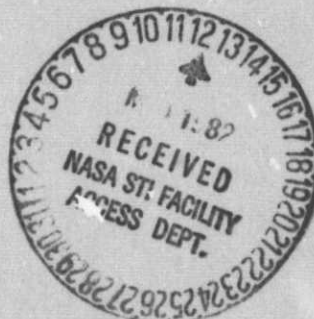
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FINAL REPORT

BY

M. P. PAUL

APRIL 1, 1982



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DEPARTMENT OF INDUSTRIAL EDUCATION

AND TECHNOLOGY

ALCORN STATE UNIVERSITY

LORMAN, MISSISSIPPI 39096

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PERIOD OF MEASUREMENT COVERED IN THE REPORT
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ABSTRACT

Measurement of integrated columnar electron content and total electron content for the local ionosphere and the overlying protonosphere via Faraday rotation and group delay techniques have proven very useful. To accomplish these objectives, a field station was established on the Alcorn State University campus having the geographic location of 31.5°N Latitude and 91.06°W Longitude.

A polarimeter receiving system was set up in the beginning to measure the Faraday rotation of 137.35 MHz radio signal from geostationary satellite ATS-3 to yield the integrated columnar electron content of the local ionosphere. The measurement was continued regularly since 1974 and the analysis of the data thus collected provided a synopsis of the statistical variation of the ionosphere along with the transient variations that occurred during the periods of geomagnetic and other disturbances.

In 1976 the scope of this polarimeter receiving system was increased by adding another polarimeter and a group delay receiver to measure Faraday rotation of 140 MHz signal and the group delay of the 1 MHz phase modulation of 140/360 MHz pair of frequencies of ATS-6 during its third phase when the satellite was positioned on 140°W Longitude. The received data were used to measure simultaneously the integrated columnar electron content and the total electron content for the ray path extending from the ground-based receiving point up to a point just beneath the satellite. The data thus collected were partially analyzed to study the diurnal and seasonal variations of the local ionosphere and the protonosphere.

Polarimetric measurement of the integrated columnar electronic content of the ionosphere under extraordinary circumstances e.g., artificial aeronomic perturbation in the ionosphere, have proven to be very useful. A cooperative experiment with the Radio-science Laboratory of Stanford University, Stanford, California, was conducted on the Florida east coast during the launch of the High Energy Astrophysical Observatory (HEAO/C) by the Atlas/Centaur rocket. Four polarimeters were deployed at four neighbouring but strategic locations for monitoring the total ionospheric electron content via measuring the Faraday rotation of the 136.14 MHz radio transmission of the Italian geosynchronous satellite SIRIO. The measurement started twentyfour hour before the launch and was continued twentyfour hour after the launch. The results thus obtained revealed a wealth of information about the temporal and spatial evolution of the "ionospheric hole" caused by the rocket exhausts as has been described in our Progress Report IV (Paul 1980).

The ambitious research project was set up and completed according to plans and schedules and the results obtained were presented in many regional, national and international meetings and were published as full papers in proceedings of the symposia and in professional journal and thereby has earned a great deal of credibility.

The research project was sponsored by the National Aeronautics and Space Administration and the financial support and cooperation that were received during this period are gratefully acknowledged

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INTRODUCTION

Ionosphere plays a very important role in long-distance radio communication. When a radio signal passes through the ionosphere, several signatures, e.g., fading due to the rotation of its plane of polarization, retardation, dispersion, scintillation, attenuation, etc., are impressed upon the signal by the ionosphere. For satisfactory transionospheric radio communication a predetermined knowledge of these effects is essential.

The statistical behavior of the ionosphere is characterized by several measurable parameters and total electron content (TEC) is one such parameter. From the analysis of the continuously measured values of TEC a wealth of information about the whole extent of the ionosphere can be known. The measurement of this quantity has been greatly simplified with the proliferation in the number of geostationary satellites.

Along with the study of the ionospheric characteristics it is also essential to study the characteristics of the overlying medium protonosphere which is considered as the ionospheric sink during the day time and ionospheric source during the night time. Like ionosphere, protonosphere is also a dynamic medium where the concentration of H-ion predominates. The two media are electro-dynamically coupled with the characteristic exchange of charged particles between the two media. This exchange of charged particles becomes important during the periods of

transient solar phenomenon and geomagnetic disturbances.

Several experiments can be designed for studying the state of condition of the ionosphere and the protonosphere on continuous basis. Two such experiments are:

- a. Faraday rotation measurement
- b. Group delay of modulation phase measurement.

With the help of the first experiment ionospheric electron content can be measured and such measurement is carried out on a continuous basis a surveillance can be established for monitoring the state of condition of the ionosphere.

The second experiment measures the total electron content of the entire path length of the signal, i.e., from the ground-based receiving point all the way up to the point just beneath the transmitting satellite. When these measurements are carried out in conjunction with the measurement of the first kind, the contribution of the protonosphere in the measured total electron content can be computed.

Ionosphere and protonosphere are global in extent. For the purpose of modelling it is of advantage the more the number of stations from which sample data are collected and analyzed.

With these objectives as goals, a field station was set up on the Alcorn State University campus having the geographical location of 31.5°N Latitude and 91.06°W Longitude. The research project was sponsored by the National Aeronautics and Space Administration grant NGR 25 012 001. At the initial phase, which began in September, 1973, experimental arrangements were established for measuring the ionospheric electron content via Faraday rota-

tion of the 137.35 MHz plane polarized radio transmission of the geostationary satellite ATS-3. This satellite posed a very suitable look angle at this location (Azimuth 145.0° and Elevation 47.0°). The setting up of the receiving system was completed in June, 1974, and the system was commissioned into operation in the middle of July, 1974, and since then data collection was continued on more or less regular basis. The quality and analysis of the data will be discussed in a latter chapter.

The launching of the radio beacon satellite ATS-6 on May 30, 1974, heralded a new era in space exploration, especially, in the simultaneous investigation of the ionosphere and the protonosphere. Among other pay-loads, this satellite had on board transmitters transmitting at 40, 140 and 360 MHz. The 40 and 140 MHz radio signals were used for measuring their Faraday rotation while propagating through the ionosphere to yield the corresponding ionospheric columnar electron content. The 40/360 and 140/360 MHz pairs of frequencies were used to measure the group delay of 0.1 and 1 MHz phase modulation for yielding the total electron content, which is the contribution made by the entire ray path traversed by the signals emanating from the transmitting geosynchronous satellite. A simultaneous measurement of the two quantities, namely, the ionospheric columnar electron content and the total electron content yielded the contribution made by the protonosphere.

In order to take the advantage of the beacon satellite and to participate in the above-stated observational program, the scope of our experimental facilities was expanded. One group

delay receiver along with a polarimeter, antennas, strichart recorders, and other accessories were added to the exting receiving system. We started making our measurements during the third phase of ATS-6 when the satellite was positioned on 140°W Longitude. Our group delay receiving system was on air in December, 1976 and continued gathering data until December, 1977. The data that were collected, their analysis and interpretation will be presented later on.

THEORY OF FARADAY ROTATION

Faraday discovered in his pioneering work on the propagation of electromagnetic waves through an anisotropic medium that when such a wave propagates through the medium its plane of polarization rotates, the amount of this rotation depending on the strength of the pervading magnetic field and the length of the path traversed. Plane of polarization of radio signals from geostationary satellite undergoes similar rotation during its passage through the magnetoionic medium ionosphere. When the VHF plane-polarized signal from the satellite enters the birefringent ionosphere, the splits into two circularly polarized components. They rotate in opposite directions as they travel through the medium with unequal speed of propagation. Finally, as the wave emerges from the ionosphere, the two component waves recombine together to form the original wave with the direction of the plane of polarization rotated with respect to the initial direction by an amount Ω given by (Ratcliffe 1960, Paul 1975)

$$\Omega = \frac{K}{f^2} \int_0^R B N \cos \theta \, ds \quad \text{radians} \quad (1)$$

where

K = a constant = 3.75×10^3 in mks unit

f = frequency of the receiving signal in Hz

B = magnetic field strength in waber/m²

θ = propagation angle between the geomagnetic field and the ray path

N = electron density, number/m³

ds = small element of the ray path.

Since $B \cos \theta$ is a slowly varying function, it can be taken out of the sign of integration and replaced by a value evaluated at a

certain height, usually 420 km (Titheridge 1972), i.e.,

$$\langle B \cos \theta \rangle = \frac{\int_0^S N B \cos \theta \, ds}{\int_0^S N \, ds} \quad (2)$$

Hence eqn(1) can be rewritten as

$$\Omega = \frac{K}{f^2} \langle B \cos \theta \rangle \int_0^S N \, ds \quad \text{radians} \quad (3)$$

$$\text{Or } I_F = \int_0^S N \, ds = \frac{\Omega f^2}{K \langle B \cos \theta \rangle} \quad \text{electrons/m}^2 \quad (4)$$

By virtue of its dependence on the geomagnetic field component along the ray path which varies inversely as the cube of its distance from the center of the earth, the value of I_F is mostly due to the contribution up to a certain height of about 2000 km. It is the ionospheric contribution and is called the Faraday electron content.

By using the numerical values of the constants in eqn(4) as appropriate for ATS-3 at this location we can arrive at the working formula for computation. as follows:

$$\begin{aligned} I_F &= \frac{(137.35 \times 10^6)^2}{3.75 \times 10^3} \times \frac{1}{28988} \Omega \quad \text{electrons/m}^2 \\ &= 5.002 \times 10^{14} \Omega \quad \text{electrons/m}^2 \\ &= 5.002 \times 10^{14} [\varphi_0 + (\varphi_1 - \varphi_2) - (\rho_0 + \rho_1) + n \pi] \\ &\quad \text{electrons/m}^2 \end{aligned}$$

where φ_p = polarimeter phasemeter reading in degrees

φ_1 = angle between the antenna A plane and the horizontal, measured clockwise from the horizontal when looking towards the satellite

$$\varphi_1 = 45^\circ$$

$$\begin{aligned}\varphi_2 &= \text{initial calibration angle of the polarimetre} \\ &= 30^\circ\end{aligned}$$

$$\begin{aligned}\beta_0 &= \text{spin axis angle between the spin axis plane and the} \\ &\quad \text{local horizontal plane measured counterclockwise from} \\ &\quad \text{the horizontal.} \\ &= 39.2^\circ\end{aligned}$$

$$\begin{aligned}\beta_1 &= \text{off-set angle, angle between the plane of polarization} \\ &\quad \text{near the satellite and the spin axis plane} \\ &= 90^\circ\end{aligned}$$

$$\begin{aligned}\beta_0 + \beta_1 &\text{ together is called the initial polarization angle} \\ &= 129.2^\circ\end{aligned}$$

Simplifying for I_F we get

$$I_F = 5.002 \times 10^{14} (\varphi_p + 15^\circ) \text{ electrons/m}^2.$$

THEORY OF GROUP DELAY

When a wave passes through a dispersive medium, change in the phase of the wave due to the presence of the medium is given by

$$\Delta \phi = \frac{\omega}{c} \int_0^R (1 - \mu) ds \quad \text{radians} \quad (1)$$

Appleton-Hartree equation for the refractive index, μ , can be written for a collisionless magnetoionic medium under quasi-longitudinal and high frequency approximation as (Ratcliffe 1960)

$$\mu = 1 - \frac{\omega_p^2}{2\omega^2}$$

where ω is the wave frequency and ω_p is the plasma frequency. Hence eqn (1) reduces to

$$\begin{aligned} \Delta \phi &= \frac{1}{2\omega c} \int_0^R \omega_p^2 ds \\ &= 8.45 \times 10^{-7} f^{-1} \int_0^R N ds \quad \text{radians} \quad (2). \end{aligned}$$

The ATS-6 Radio Beacon Experiment (RBE) was so designed that the beacon transmitter transmitted at four different frequencies, two around VHF (140 MHz) and two around UHF (360 MHz). Let these four different frequencies be designated as

$$f_{v1}, f_{v2}, f_{u1} \text{ and } f_{u2}.$$

The phases of these four different frequencies at the receiver will be

$$\phi_{v1}, \phi_{v2}, \phi_{u1} \text{ and } \phi_{u2}$$

and the phase differences between the two pairs of frequencies is

$$\Delta \phi = (\phi_{v2} - \phi_{v1}) - (\phi_{u2} - \phi_{u1}).$$

Each of the above phases consists of two components, ϕ_T , the original phase of the wave at the transmitter and ϕ_I , that it

undergoes while traversing through the ionosphere. Hence

$$\Delta \phi = -(\phi_{IV2} - \phi_{IV1} - \phi_{IU2} + \phi_{IU1}) + (\phi_{TV2} - \phi_{TV1} - \phi_{TU2} - \phi_{TU1}).$$

Since the quantity in the second parenthesis is known from the satellite parameters, $\Delta \phi$ can simply be written as

$$\Delta \phi = \phi_{IV2} - \phi_{IV1} - \phi_{IU2} + \phi_{IU1}.$$

Hence eqn (2) can be written as

$$\begin{aligned} \Delta \phi &= 8.45 \times 10^{-7} \left(\frac{1}{f_{V1}} - \frac{1}{f_{V2}} - \frac{1}{f_{U1}} + \frac{1}{f_{U2}} \right) I_T \\ &= 8.45 \times 10^{-7} \left(\frac{n^2 - 1}{n^2} \right) f_m \cdot \frac{1}{f_v^2} I_T \end{aligned}$$

where $I_T = \int_0^R N ds$, the integrated electron content,

$$f_{V2} - f_{V1} = f_{U2} - f_{U1} = f_m,$$

f_m = modulating frequency

and $f_u = n f_v$.

For ATS-6 RBE, $f_v = 140$ MHz, $f_u = 360$ MHz, $n = \frac{f_u}{f_v} = 360/140 = 2.57$

and $f_m = 1$ MHz. Substituting all these values in eqn (3) and simplifying, it reduces to

$$\Delta \phi = 3.6645 \times 10^{-17} I_T \text{ radians.}$$

Or $I_T = 4.8 \times 10^{14} \Delta \phi \text{ electrons/m}^2$

with $\Delta \phi$ expressed in degrees. As $\Delta \phi$ can be read from the phase-meter of the group delay receiver, this determines the value of I_T .

The value of I_T is sensitive to the value of geomagnetic field strength and is independent of the layer shape and its height. Consequently the value of I_T will yield the contribution of electronic concentration along the entire ray path.

Contribution made to the TEC by electronic concentration above

the highest point in the ionosphere is the protonospheric electron content, I_p . So $I_p = I_T - I_F$.

From a simultaneous measurement of I_T and I_F , I_p can be obtained and a continuation of this measurement over time will yield its short and long term temporal variation. This is the true essence of the Radio Beacon Experiment of ATS-6

INSTRUMENTATION FOR FARADAY ROTATION MEASUREMENT

The experimental arrangement consists of nine element 12.1b gain crossed yagi antenna electronically switched between its A and B planes, a polarimeter, slow (fixed) and high (variable) speed stripchart recorders as is shown in Fig.1 . The antenna and the polarimeter were manufactured by the Aldi Research Corporation, Palo Alto, California. The antenna with its eight feet boom sits on a high pedestal and can be aligned in the satellite directions with its counter weights. The signal received by the antenna is sampled by the sampling switch and is amplified by the preamplifier which is generally mounted on the antenna mast. The sampling switch and the preamplifier are housed in the same box. The output of the preamplifier is applied to the input of the polarimeter receiver. The receiver has BFO turning mechanism and the signal is processed by a signal processor housed in the same cabinet. The low frequency signals are then recorded by high speed (6"/hr.) and low speed (1/2" hr) pen recorders. The high speed recordings are the high resolution records and the low speed recordings are the diurnal records without any retrace. Most of our data analysis of the diurnal records. The complete description of the experimental arrangements along with complete details of the instruments are given in our previous reports (Paul 1975, Antoniadis, 1974).

INSTRUMENTATION FOR GROUP DELAY MEASUREMENT

The experimental arrangement for group delay measurement is shown diagrammatically in Fig. 2. It consists of a pair of antennas, one VHF crossed Yagi antenna - nine elements and about 12 db. gain, the other one a UHF left circularly polarized helical antenna. The VHF Yagi antenna receives the pair of frequencies around 140 MHz and the UHF antenna receives the pair of frequencies around 360 MHz. They pass through the sampling switch and the preamplifiers. The outputs of the preamplifiers are applied to the inputs of the group delay receiver.

The group delay receiver is shown in Fig. 3 as a block diagram. It is a triple detector band squeezing receiver. The received frequencies are translated to lower frequencies without disturbing their relative phase relationship. The two channels are completely identical with each other except an additional converter amplifier in the UHF channel as seen in Fig. 3. The received signals, consisting of the carriers and the sidebands are applied to the first detector. The first mixer translates the signals to a lower frequency range. These are fed to the second mixer through a broadband pass amplifier. Here the two components are translated in frequency in such a way that their frequency difference, i.e., the modulation frequency, is decreased. Since the operation is performed simultaneously, the two new modulation frequencies are identical. The signal is then passed through a second IF amplifier, and then to a third mixer, where it is translated further down. The signal is then passed through a third IF amplifier.

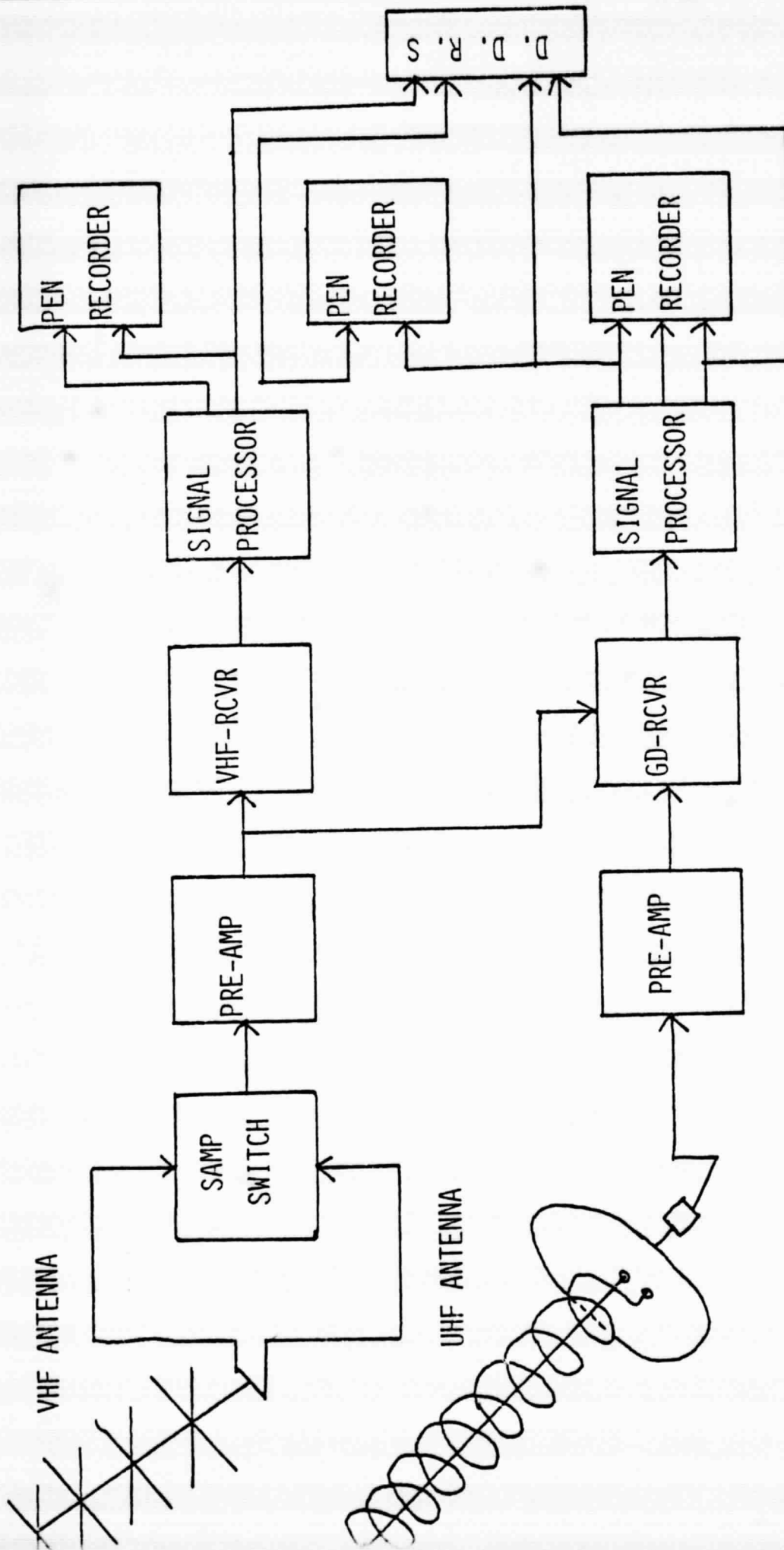


FIG. 1. BLOCK DIAGRAM OF POLARIMETER AND GROUP DELAY RECEIVER SYSTEM

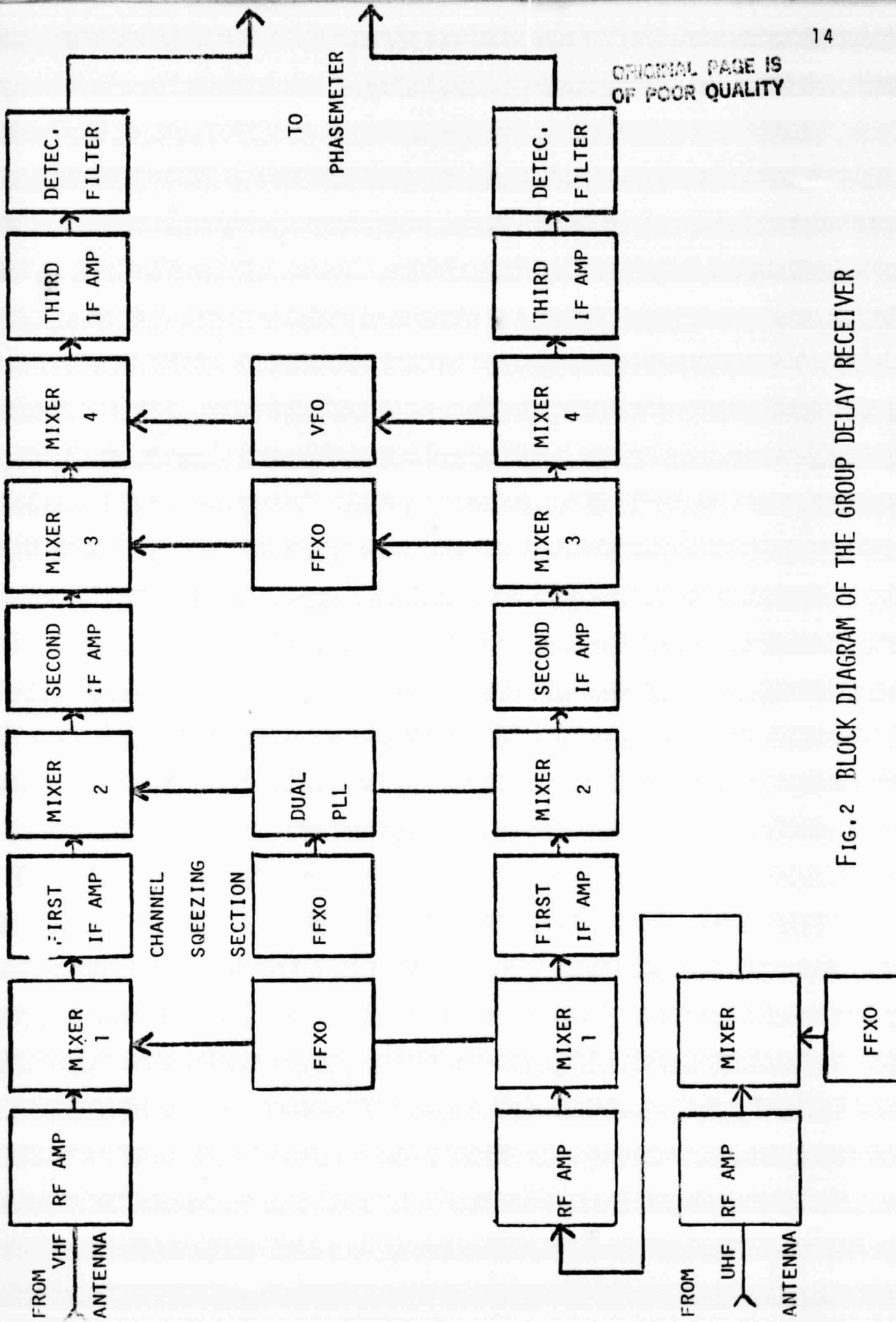
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FIG. 2 BLOCK DIAGRAM OF THE GROUP DELAY RECEIVER

The signal is next fed to a square law detector at the output of which the new modulation frequency appears. The phases of the output signals from the two channels are compared in a phasemeter whose output is a voltage directly proportional to the phase difference and can be recorded continuously. Further details of the group delay receiver are given in our earlier reports (Paul 1978, Antoniadis 1976).

DATA AND DATA ANALYSIS

As described earlier our Faraday rotation measurements started in July, 1974, and since then our data acquisition continued without much interruption. These data were collected mostly in the form of fast speed and slow speed stripchart recordings. The slow speed chart recordings, called the diurnal records, were analyzed in great details. These data showed the diurnal and seasonal patterns of Faraday columnar electron content at this geographic location. A general representation of our data were given in our previous reports (Paul 1976a, 1976b). These analyses show that the Faraday electron content has an usual variation pattern at this location. It has the minimum value during the predawn periods, steep rise during the postdawn periods followed by the maximum peak values which generally occur during the post noon periods, i.e., around 14 hours local time. During the late evening and dusk periods, ionospheric electron content decreases gradually and the ionosphere remains generally not so heavy during midnight periods. These variations also display occasional post midnight maxima which are explained along with others, by the $E \times B$ drift of the ionospheric plasma during the noturnal periods.

Our field station is a typical midlatitude station and the variational trend of ionospheric electron content is consistent with the values obtained at such other stations, especially during the quiet periods.

We have also analyzed a few ionospheric storms as accompanied by corresponding geomagnetic disturbances. These geomagnetic disturbances were identified by comparing them with the variations of the usual geomagnetic indices, e.g., three-hourly values of K_p , daily values of interplanetary index A_p , and hourly values of equatorial Dst index, which is defined as the longitudinal average of the northward horizontal component of the earth's geomagnetic field around the equator.

Significant changes in the ionospheric columnar electron content values were observed during the storm-time values as compared with the quiet-time values. These storm-time values usually have three phases - early phase, main phase and the recovery periods. Ionospheric columnar electron contents as obtained on many storm days during the periods July 16, 1974 to April 30, 1976, were analyzed and have been described fully in our previous progress report (Paul 1976).

Monitoring the state of condition of the ionosphere via measuring its Faraday columnar electron content has proven to be very useful. It has been discovered (Mendillo and Forbes, 1978 and literatures cited therein) that rocket exhausts cause excessive recombination of ionospheric species causing the ionospheric concentration to decrease sharply. Thus sudden disappearance of the ionosphere has been termed as ionospheric hole. Its usefulness in the fields of ionospheric physics and radio astronomy has been widely recognized.

Extensive theoretical works (Bernhardt, 1976) have been carried out to study the temporal and spatial evolution of this

hole in the horizontal and vertical directions.

A cooperative experimental observation with the Radioscience Laboratory of Stanford University was undertaken. The launching of the High Energy Astrophysical Observatory (HEAO/C) by the Atlas /Centaur rocket burn was selected for investigating experimentally the aeronomic perturbations by monitoring the columnar electron content via Faraday rotation measurement of the 136.14 MHz radio signal of the Italian geostationary satellite SIRIO.

Four polarimeters along with all the accessories were deployed at four neighbouring but strategic locations on the east coast. Columnar electron contents were measured at these locations starting from twentyfour hours before the launch and continuing twentyfour hours after the launch. Complete description of the experiment, data collected and their analysis have been described in our earlier report (Paul, 1980).

The launching of radio beacon satellite ATS-6 on May 30, 1974 heralded a new era in space exploration. Among other payloads, this geosynchronous satellite carried on board radio transmitters- transmitting radio signals at 40, 140, and 360 MHz. A simultaneous measurement of Faraday rotation of 140 MHz and the group delay measurement of 1MHz phase modulation of the pair of frequency 140/360 MHz provided a unique method for measuring the contribution of the protonosphere to the total value of integrated electron content thereby providing a unique method of studying the variability of the protonosphere in real time from ground-based station.

Useful data of group delay measurements were collected covering the period December, 1976 to June, 1977, when ATS-6

was positioned on 140°W longitude. These data were collected by high and slow speed strip chart recorders. The diurnal records (the slow speed record) were digitized and analyzed for this study. The results thus obtained were consistent with results obtained at other midlatitude stations - especially at Boulder, Colorado (Paul 1980, Davies and Paul 1980 and Paul 1980). The main feature of the results is that the protonospheric contribution show no or very little diurnal variability. Complete details and pertinent discussions have been given in our previous progress report (Paul, 1980).

DISCUSSION

Over the years when the experiment was conducted good quality Faraday rotation and group delay measurements data were collected. These data were in the form of high and low speed strip chart recordings. The analysis of diurnal records provided an opportunity to study the dynamic variability of the local ionosphere and the protonosphere in real times. Diurnal and seasonal variations of ionospheric electron and the total electron contents were studied along with their sudden variations during geomagnetically disturbed periods and other special conditions. The results thus obtained were found very useful and consistent and were presented in many domestic, national and international professional meetings proceedings and professional journals (Paul et al 1977, Paul and Leitinger 1978, Davies and Paul 1980, Paul 1980). All these results provided a picture of the statistical behavior of the local ionosphere and the overlying protonosphere. The data are being stored in files for future reference.

ACKNOWLEDGEMENT

Our research project for measuring integrated columnar electron content and total electron content via Faraday rotation and group delay techniques were sponsored by the National Aeronautics and Space Administration. The data gathered thus far have been partially analyzed and presented in my regional, national and international professional meetings and were highly appreciated. The results were also published as full papers in the symposium's proceedings and professional journals. The rest of the data are being stored on files in digitized and analog formats for future reference.

This experiment is a typical one in space science and in passive satellite reception. The conduction of such an exciting experiment on this university campus is considered as a great landmark and generated considerable enthusiasm among students, faculties and neighbouring communities and has enhanced the reputation of the university in the international sphere of research.

The research project was accomplished as per schedule and plan and the accomplishments achieved so far is considered as highly satisfactory. The financial support and cooperation that we have received from the National Aeronautics and Space Administration are gratefully acknowledged.

The encouragement and cooperation that were received from the university administration, department head and faculties, by the principal investigator and the student workers during the

entire course of the research project are also gratefully acknowledged.

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